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MINERALOGY AND DEEP-CLEANING OF CANADIAN HIGH SULPHUR COALS
REPORT No. 2 - DONKIN-MORIEN SEAM

G.I. Mathieu
Mineral Processing Laboratory

February 1987

Project: 30.79.01
High Sulphur Coal

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DIVISION REPORT MSL 87-47 (IR)

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by

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ABSTRACT

Because of environmental and energy problems, a revolution is taking place in the physical beneficiation of coal. This requires advanced developments in multidisciplinary sciences and engineering technologies, in order to solve the variety of problems that face the coal preparation engineer in producing an environmentally acceptable fuel at an economically competitive price.

The processing of fine coal, for instance, has been a long-standing problem in the industry. This is partly attributable to insufficient knowledge of the mineralogy of coal and associated minerals, as well as inadequate application of beneficiation methods. In this study, attempts were made to better characterize a Canadian coal using microscopic and ancillary techniques, and subsequently to derive from the mineralogical findings the best procedure for ultimate cleaning of this coal.

The sample under investigation contains 7.2% ash occuring mainly as fine clay minerals and 1.49% sulphur in pyritic form. The pyrite grains are extremely small with a mean size of 15 µm, while the clays are only slightly larger at about 30 µm. Using progressive grinding and processing by flotation and magnetic separation under the most satisfactory conditions, it was nevertheless possible to obtain a coal product analyzing 1.1% ash and 0.16% pyritic sulphur with an 84% thermal yield. Flotation and high-gradient magnetic separation were tested both as alternative and complementary coal beneficiation methods and their respective merits are assessed in the study.

A good correlation was obtained between the mineralogy, washability and flotation-magnetic separation data throughout the testwork.

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Keywords: Coal, Mineralogy, Flotation, Magnetic Separation

MINÉRALOGIE ET NETTOYAGE EN PROFONDEUR DES CHARBONS CANADIENS À HAUTE TENEUR EN SOUFRE

par

G.I. MATHIEU*

RÉSUMÉ

Conséquence des problèmes environnementaux et énergétiques que nous connaissons, une révolution s'opère dans le domaine de l'enrichissement physique du charbon. Cette révolution nécessite des recherches approfondies à l'àide de sciencies multidisciplinaires et de technologies d'ingénierie, de façon à résoudre une vaste gamme de problèmes auxquels font face les ingénieurs en préparation du charbon qui tentent de produire un combustible acceptable pour l'environnement et à un coût compétitif.

Le traitement du charbon fin par example est un problème qui a persisté très longtemps dans l'industrie. Cet état de fait est en partie dû à une connaissance insuffisante de la minéralogie du charbon et des minéraux qui lui ont associés, et d'une application inadéquate des méthodes d'enrichissement. Le but de cette étude fut donc de mieux caractériser le charbon canadien à l'aide d'observations au microscope et d'autres techniques auxiliaires, de façon à déduire à partir de ces observations minéralogiques les meilleures procédures pour purifier ce charbon.

L'échantillon analysé contenait 7,2 % de cendres, généralement constituées de minéraux fins argileux, et de 1,49 % de soufre sous forme pyritique. Les grains de pyrite sont extrêmement fins avec un diamètre moyen de 15 µm, alors que les argiles sont légèrement plus gros, à environ 30 µm. Sous les conditions les plus satisfaisantes, il a été néanmoins possible, en utilisant un broyage et par séparation magnétique, d'obtenir un produit du charbon présentant 1,1 % de cendres et 0,16 % de soufre pyritique, avec un rendement thermique de 84 %. Les séparations par flottation et à haut gradient magnétique ont été testées par des méthodes d'enrichissement du charbon tant alternatives que complémentaires, et leurs qualités respectives sont évaluées dans cette étude.

Une bonne corrélation a été obtenue entre les données de minéralogie, de séparation par flottation et magnétique, et de capacité d'être lavée du charbon, pour l'ensemble de l'étude.

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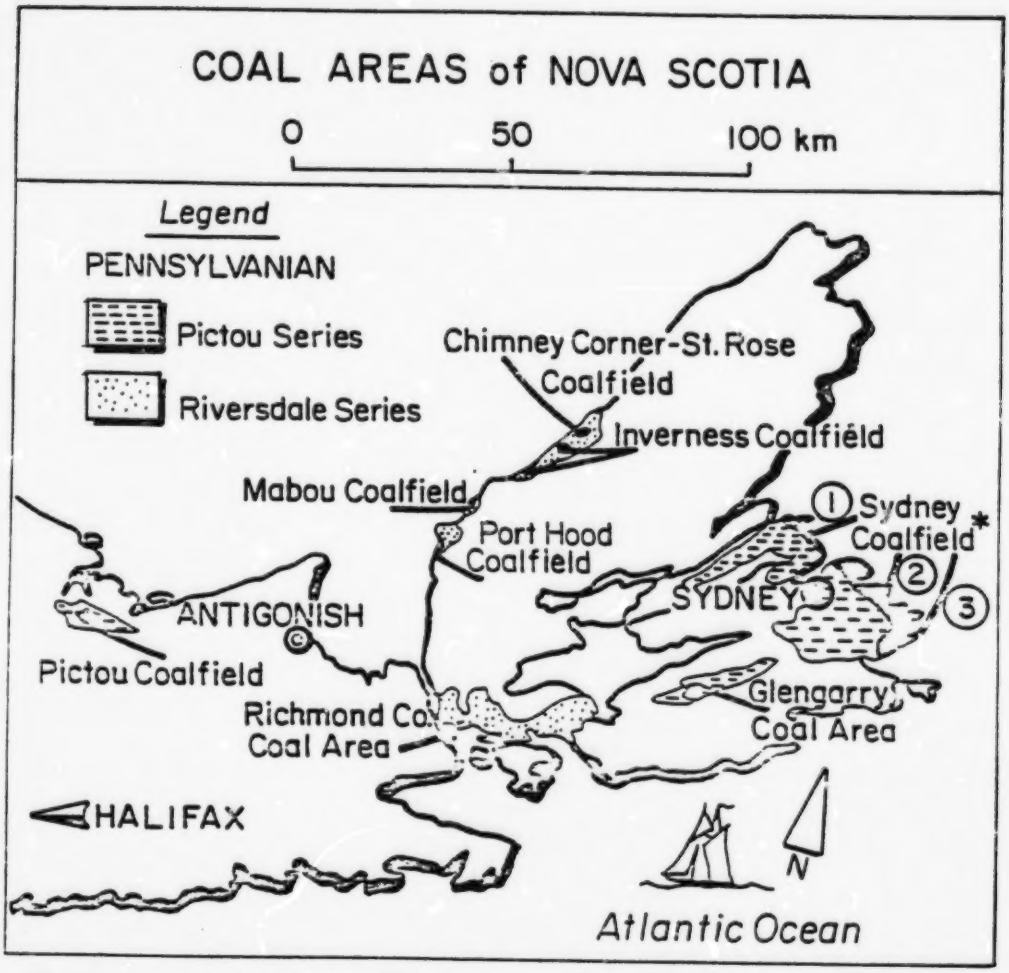
Mots-clés: charbon, ménéralogie, flottation, séparation magnétique



* Sydney coalfield: ① - Prince, ② - Lingan, ③ - Donkin

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INTRODUCTION

Background Information

Coal is abundant in eastern Canada with total reserves established at nearly 5 billion tonnes, but these are high in sulphur content at 2-10% by weight. The Cape Breton Development Corporation (DEVCO) is by far the major coal producer of the Atlantic region with two mines in operation and another under development, all located in the Sydney coalfield of northeastern Nova Scotia (see map on p. iii). Our research program, which is primarly aimed at reducing sulphur (and asn) in eastern coal products, was initiated on DEVCO coals because of the company's important position in the Canadian and overseas markets and its current expansion program, as is shown by the company's current production and predicted figures for the next decade (Table 1). Estimates of the sulphur content of the deposits are also given.

Table 1 - DEVCO's Coal Production and Expansion

Mines	Reserves (millions tonnes)	Total sulphur analysis (% St)	Production (MT/year) 1986	Production (MT/year) 1996*	Life expectancy (years)
Lingan	100	1.8-2.0	1.6	3.0	65
Prince	70	4.5-5.0	1.2	1.0	70
Donkin	450	2.5-5.0	-	1.5	300
Total	620	3.0	2.4	5.5	-

*Depending on market

Since part of the future production shall be used for the conversion of Nova Scotia's thermal generating stations from oil to coal (possibly in the form of coal-water slurry), lower sulphur products will be required to meet the proposed National Guidelines on sulphur dioxide (SO_2) emissions, i.e., 0.5-1.6 lb/10^6 BTU (depending on the coal source), which corresponds to 0.4-1.4% sulphur content for 14 000 BTU/lb coal. To satisfy such requirements, essentially all the pyritic sulphur will have to be removed from the DEVCO coals. Furthermore, if the finished coal products are to be used as a burning slurry, a high reduction of the other mineral matter will also be necessary, as well as rigid size control.

Purpose and Scope of Research

The objective of the research project is twofold, i.e. (1) to better characterize the eastern coals by extensive chemical and mineralogical studies, and (2) to use the data obtained for selecting and testing the most appropriate physical cleaning methods. The first portion of the experimental work involved the coal from the two DEVCO mines in operation, namely Lingan and Prince; it was reported in 1986[1].

The current study was made on the Donkin-Morien seam, a high-volatile "A" bituminous coal analyzing 6 to 12% ash and approximatively 3% sulphur. The coal characterization included proximate and ultimate chemical analyses, dense liquid (float-sink) separations and petrographic studies. These were carried out at the Atlantic Coal Institute (ACI), Nova Scotia[2]. The coal beneficiation procedure was developed and tested at the Canada Centre for Mineral and Energy Technology (CANMET). It consisted of progressive grinding and processing by froth flotation and high-gradient magnetic separation. The two cleaning techniques were tried either as alternative or complementary methods. The testing pattern permits one to compare and assess the merit of each additional cleaning stage, as the beneficiation progresses.

CHEMICAL ANALYSIS, PETROLOGY AND MINERALOGY

In preparation for intensive cleaning of a coal, it is imperative to acquire an adequate knowledge of its chemical and mineralogical composition, in particular, the concentration, nature and association of the ash and sulphur-bearing minerals, as well as their respective liberation from the macerals. The Donkin-Morien coal has been characterized principally by Birk and Associates[2] using a 100 kg run-of-mine sample collected from various development sites of the mine. A representative head sample was riffled from this lot, prepared and analyzed along standard ASTM methods with the following results.

Table 2 - Chemical analysis of Donkin-Morien coal

Sample	Type of analysis		
	Proximate	Sulphur forms	Ultimate
ROM Coal	C (fixed) - 51.7% Volatiles - 36.5% Ash - 11.7% Moisture - 0.0%	Pyritic - 1.80 Organic - 0.87 Sulphate - 0.06 Total 2.73	C (total) - 70.7 Oxygen - 6.1 Hydrogen - 4.7 Nitrogen - 1.2
Ash*	Fe_2O_3 = 40.8%, SiO_2 = 21.4%, Al_2O_3 = 16.5%, CaO = 5.9% K_2O = 1.0%, Na_2O = 0.6%, MgO = 0.6%		

*From low temperature ashing in presence of oxygen

From the data on the sulphur forms with 0.87% S (organic), it is inferred that almost one third of the sulphur is bound to the molecular structure of the coal macerals and thus not removable by physical means. Another finding is the high content of Fe_2O_3 in the ash product, which indicates the presence of iron-bearing minerals other than pyrite and thus suggest magnetic separation as an alternative to flotation for removing the gange minerals from the coal values.

Petrologically, the Donkin-Morien coal contains a high proportion of vitrinite, less exinite and semi-fusinite, and minor concentration of inertinite, consisting particularly of fusinite, macrinite and micrinite. The approximate abundance of each specific maceral is given in Table 3 and their definition follows.

Table 3 - Maceral composition of Donkin-Morien coal (after Birk et al.)[2]

Category	Group/species		Volume (appr. %)	Texture and morphology
Reactive (~85% by vol.)	Vitrinite		73.0	1. Layered 2. Cellular 3. Lenses 4. Spherical and a elongated grains. (The macerals have intergrowths and inclusions of clay, pyrite and quartz.)
	Exinite	sporinite	5.0	
		resinite	4.5	
		cutinite	0.5	
	Semi-fusinite		2.0	
Inert (~10% by vol.)	Semi-fusinite		4.5	
	Inertite	fusinite	1.5	
		macrinite	1.0	
		micrinite	2.0	
		others	1.0	

Vitrinite is a maceral group derived from the woody component of the coal with reflectance between those of exinite and inertinite. Exinite is an hydrogen-rich maceral group having a low reflectance, while inertinite comprises non-reactive, highly reflective macerals. Sporinite, resinite and cutinite are classified in the exinite group. They consist respectively of derivatives from the waxy coatings (exines) of spore and pollen, resinous secretions and exidates of plant cells, and cuticles characterized by serrated edges and high relief. Macrinite is an inertinitic maceral of uncertain origin with irregular shape and high reflectance, while micrinite is of the same nature but smaller in size and more granular in appearance. Fusinite is a maceral distinguished by well-preserved original form of plant cell wall structure with open or mineral-filled cavities, while semi-fusinite is a transitional specie between vitrinite and fusinite with intermediate reflectance and cell wall structure less defined.

Polished sections of coal fragments and mounts of low-temperature ash (LTA) residues were extensively examined by the mineralogy groups of AIC and CANMET. Practically no coarse-grained host rock was observed with the coal. On the other hand, fine clay minerals (kaolinite and illite in particular), pyrite and quartz were often seen finely dissiminated in the macerals.

The clay minerals were generally in stratified forms (lamellae, lenses and veinlets) and as cellular replacement in the coal structure. Pyrite, the only metallic mineral observed in significant amount, occurs as tiny crystals, either solitary or grouped as clusters and framboids, as well as globules and cauliflowers. Minor quantities of pyrite were observed as small patches and lenses, occasionally filling coal structural cavities. Sulphur is also present in organic form and as iron sulphate. Further details on the texture, concentration and size of the minerals associated to coal are given in Table 4.

Table 4 - Minerals identified in the Donkin Morien coal (after Birk[2] and Hugnson[3],*)

Category/species		Volume (%)		Texture and morphology
		+20 µm	-20 µm	
Clays (~3% by vol.)	Kaolinite and illite	1.6	1.4	- Lamellae, lenses and veinlets parallel to layered coal - Intergrowths, inclusions and fillings of cellular structure - Individual and agglomerated grains.
Oxides, carbonates and silicates (<1.0%)	Quartz calcite chlorite and others	0.2 (Traces) (Traces) (Traces)	0.3	- Fragments and flakes - Inclusions and intergrowths
Sulphides (~1% by vol.)	Pyrite	0.0	0.23	Solitary crystals: euhedral, subhedral and pinpoints
		0.14	0.24	Crystal groups: clusters, framboids and lenses
		0.14	0.20	Globules and cauliflowers
		0.03	0.01	Patches, cell filling and replacement
Iron sulphate		0.05		Alteration of pyrite
Organic sulphur		0.7		Solid solution in coal macerals

A number of microphotographs were taken to illustrate the features of the coal petrology and mineralogy. Figures 1 to 4 show the structure of the coal, namely layered, cellular and grained (spheres and lenses). The next set of four pictures is devoted to the occurrences of the clay minerals, mainly as strata, lamelleas, individual and aggregated grains, all in coal matrix. Another series of microphotographs (No. 8 to 11) represent pyrite crystals and aggregates at increasing magnification, while Figure 12 shows a dot map of organic sulphur in a coal field.

Fig. 1 - Various coal macerals shown as layered shades of grey (x45).

Fig. 2 - Stratified coal seams with some bands of cellular coal (light grey); x45.

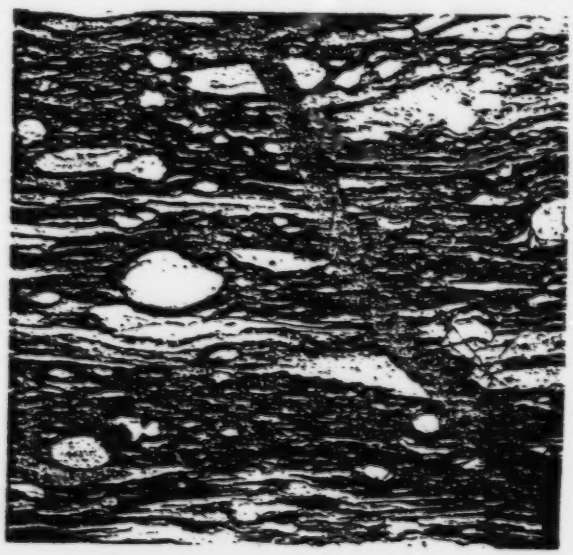

Fig. 3 - Spherical and elongated grains of coal in an organic matrix (x45).

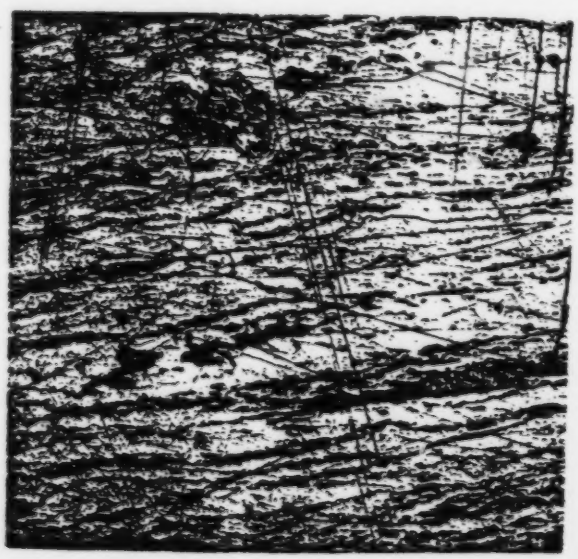

Fig. 4 - Lenses of plant material (medium grey). Plane polarized reflected light; 42x.

Fig. 5 - Lamellea of clay minerals with lenses of plant minerals (both white). Plane transmitted light; 42x.

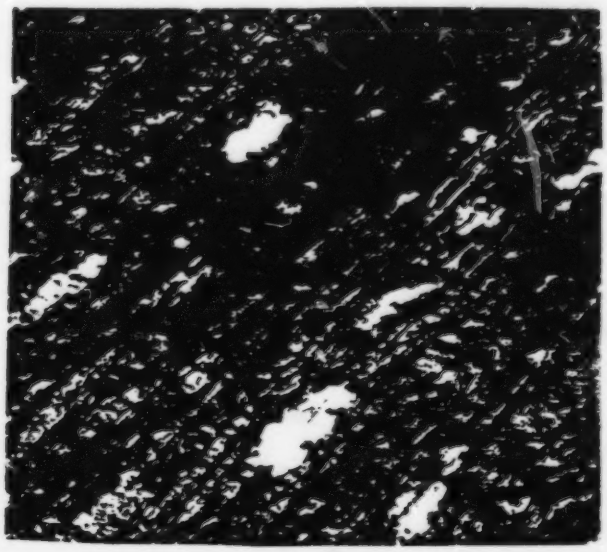

Fig. 6 - Stratified clay minerals (white to shades of grey) in coal fields (darker). Plane polarized transmitted light; 165x.

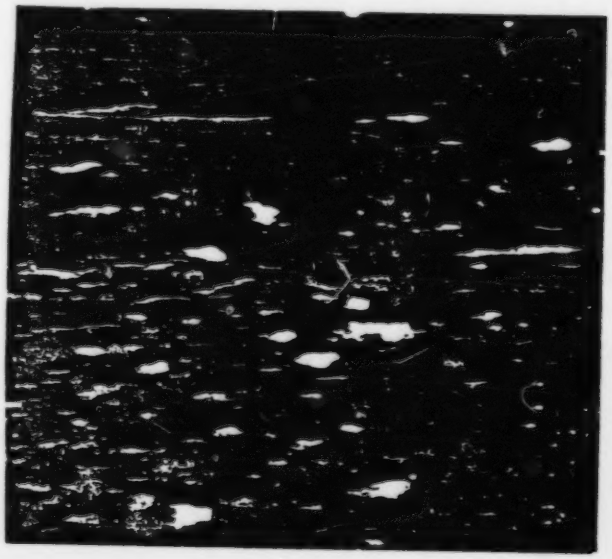

Fig. 7 - Elongate clay grains in a coal matrix. Plane transmitted light; 165x.

Fig. 8 - Aggregate of grey clay surrounded by lighter colored coal. Plane incident light; 265x.

Fig. 9 - Stratified pyrite (white) in coal seams. Plane incident light; 42x.

Fig. 10 - Clusters and framboids of pyrite grains (white) in coal. Plane incident light; 83x.

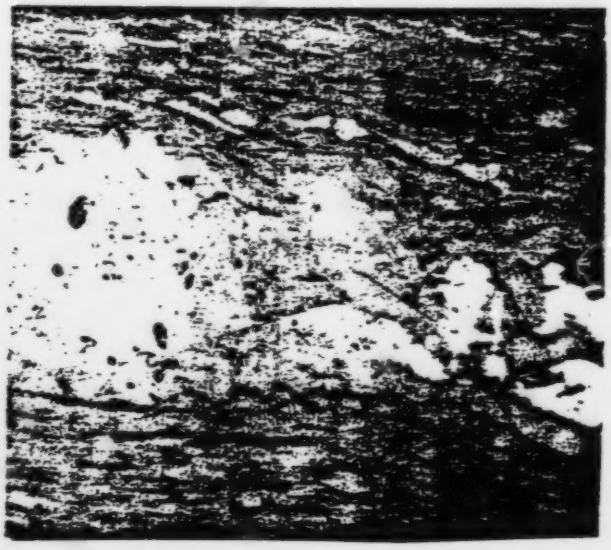

Fig. 11 - Agglomerated pyrite in light grey banded coal (x415).

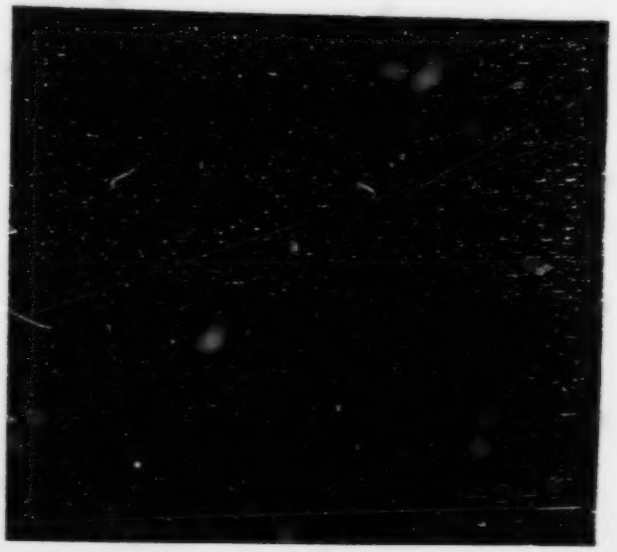

Fig. 12 - Sulphur dot map of coal area indicating the presence of organic sulphur.

In conjunction with petrographic studies, many size measurements were made on the pyrite by the ACI staff[2]. Birks reported that this mineral generally accounts for less than 5% of the grains in which it is present. Based on a system developed by Stack et al.[5], he proposed the following pyrite size distribution:

Table 5 - Pyrite size distribution

Grains observed	Group	Pyrite content	Frequency %
Free pyrite	1	>80%	0.2
Pyrite-rich	2	80 - 50%	0.4
	3	50 - 20%	1.0
Pyrite-poor	4	20 - 5%	3.4
	5	5 - 0%	95.0

Therefore, both the grain composition and the average size of pyrite (which was established at 25 to 30 microns) have led Birk to conclude that its liberation would require extremely fine pulverization[2]. CANMET measurements suggested that the pyrite on the sample to be beneficiated was even finer with an average size of less than 15 µm. Hughson has also established a dimensional pattern of the clay minerals with the majority of the grains within 10 to 50 µm and a mean size of about 30 µm.

COAL WASHABILITY AND LIBERATION CHARACTERISTICS

Conventional float-sink tests were made on nine sieved fractions of the Donkin-Morien coal at the specific gravities of 1.30, 1.35, 1.40, 1.45, 1.50, 1.60, 1.70, 1.80 and 2.00. The purpose was to compare the washability data of relatively large (12.5 x 4.76 and 4.76 x 1.19 mm), intermediate (1.19 x 0.60, 0.60 x 0.35 and 0.35 x 0.15 mm) and fine (0.15 x 0.074, 0.074 x 0.037, 0.037 x 0.026 and minus 0.026 mm) sizes. Ash, sulphur and calorific values were determined on the float and sink products. The results are reported in detail elsewhere, 2,6. For this report, the analyses and thermal yields of the coarse, medium and fine fractions were computed on a cumulative basis. These data tabulated Appendix I, served to draw a series of curves (Fig. 13) which illustrate the increasing liberation of the ash-bearing and pyritic minerals as a function of fineness. For a better view of the trends, lines representing the ash and sulphur contents in the coarsest and finest individual size fractions, i.e. 12.4 x 4.7 and minus 0.026 mm, are also shown in the graph.

Table 6 - Summary of float-sink results (cumulative basis)

Sized fractions	Specific gravity	Mass %	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
Coarse: 12.5 x 4.76 and 4.76 x 1.19 (mm)	1.30	76.23	1.78	1.58	14717	19.9	36.7	81.4
	1.35	83.91	2.19	1.77	14630	27.0	45.3	89.1
	1.40	86.62	2.39	1.83	14591	30.4	48.5	91.7
	1.45	89.96	2.79	1.94	14522	36.8	53.4	94.8
	1.50	90.82	2.90	2.01	14502	38.6	55.6	95.6
	1.60	92.63	3.25	2.15	14439	44.1	60.8	97.1
	1.70	93.23	3.40	2.21	14411	46.5	63.0	95.7
	1.80	94.38	3.78	2.32	14342	52.4	66.6	98.2
	2.00	95.38	4.18	2.41	14271	58.5	70.2	98.8
	Sink	4.62	60.82	21.03	3540	41.9	29.8	1.2
	Head (C)	100.00	6.81	3.28	13774	100.0	100.0	100.0
Medium: 1.19 x 0.60 0.60 x 0.35 and 0.35 x 0.15 (mm)	1.30	73.09	1.05	1.41	14488	11.9	38.9	78.6
	1.35	83.47	1.47	1.57	14376	19.1	49.6	89.0
	1.40	87.17	1.70	1.66	14330	23.0	54.6	92.7
	1.45	89.88	1.95	1.77	14285	27.3	60.0	95.2
	1.50	91.02	2.11	1.79	14225	29.8	61.8	96.3
	1.60	92.81	2.42	1.90	14203	34.9	66.5	87.8
	1.70	93.62	2.61	1.94	14170	38.1	68.5	98.4
	1.80	94.34	2.84	1.98	14133	41.7	70.7	98.9
	2.00	95.98	3.47	2.09	14027	51.7	75.5	99.7
	Sink	4.22	73.45	15.33	2041	48.3	24.5	0.3
	Head (C)	100.00	6.43	2.65	13522	100.0	100.0	100.0
Fine: 0.15 x 0.074, 0.74 x 0.037 and 0.037 x 0.026 (mm)	1.30	75.38	0.91	1.51	14740	9.88	35.21	81.23
	1.35	83.06	1.20	1.64	14689	14.32	42.06	89.19
	1.40	86.44	1.39	1.71	14656	17.27	45.73	92.62
	1.45	88.48	1.51	1.76	14634	19.29	48.09	94.66
	1.50	90.25	1.83	1.84	14577	23.43	51.46	96.18
	1.60	91.45	2.08	1.91	14533	27.44	54.04	97.16
	1.70	92.06	2.23	1.96	14506	29.62	55.82	97.63
	1.80	92.68	2.48	2.01	14464	33.12	57.55	98.00
	2.00	94.05	3.05	2.16	14364	41.29	67.76	98.76
	Sink	5.95	68.49	20.23	2846	58.71	37.24	1.24
	Head (C)	100.00	6.94	3.21	13679	100.00	100.00	100.00

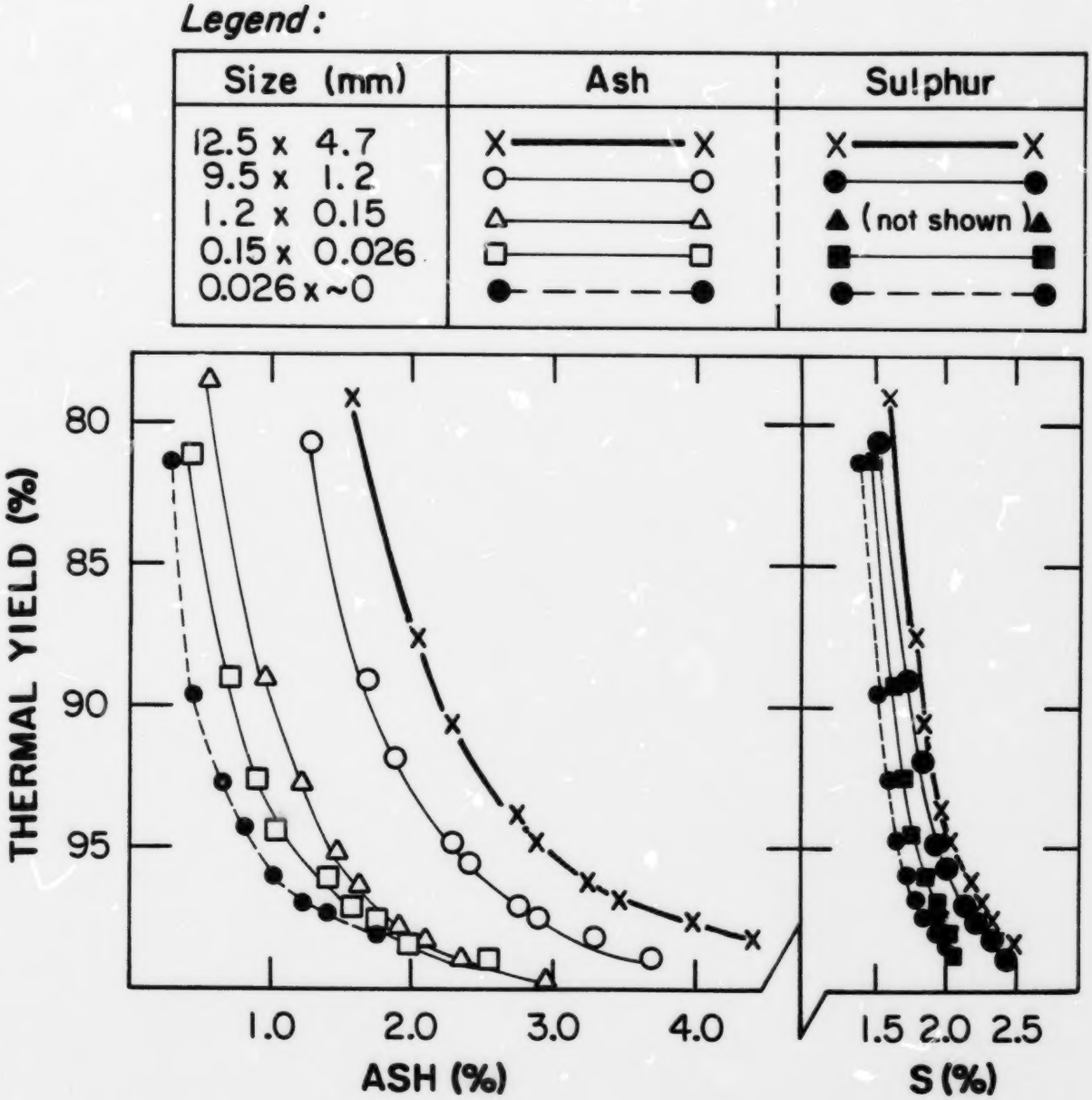

Fig. 13 - WASHABILITY CURVES OF COAL SIZED FRACTIONS

Each curve permits to extrapolate the thermal yield of a sized coal product for a given concentration of ash and sulphur and vice versa, (i.e. the ash and sulphur content corresponding to given yields). To demonstrate the benefits of the fine comminution for cleaning the Donkin-Morien coal, examples of constant yield coal products as function of size are given in Table 6 (Part 1). Yields corresponding to various coal grades are also tabulated (Part 2).

Table 7 — Effect of size on clean coal grade and thermal yield

1. Ash and sulphur variation at constant yield

Thermal yield %	Clean coal analysis					
	% Ash			% Sulphur		
	Coarse (sized fractions)	Medium (sized fractions)	Fine (sized fractions)	Coarse (sized fractions)	Medium (sized fractions)	Fine (sized fractions)
95	2.8	1.9	1.5	1.95	1.75*	1.80
90	2.2	1.5	1.1	1.75	1.60*	1.65
85	1.9	1.3	0.9	1.65	1.50*	1.55

* Lower sulphurs partly attributable to a lower head.

2. Yield variation at constant ash and sulphur

Clean coal analysis		Thermal yield (%)		
% Ash	% S	Coarse (12.5 x 1.2 mm)	Medium (1.2 x 0.15 mm)	Fine (0.15 x 0.026 mm)
2.8	2.0	95	99	99
2.2	1.8	90	97	98
1.9	1.7	85	95	97

Upon examination of these results and of the preceeding curves with lower slopes near the x axis, it appears that the best approach to clean the coal would consist of removing ash and sulphur at intermediate size with high thermal yield (i.e. along the bottom part of the washability curve) and then to regrind for further beneficiation along another curve closer to the origin. A procedure was devised to cope with these observations and to allow for comparison of results after the various stages of cleaning.

COAL BENEFICIATION STUDIES

Sample Preparation

A representative raw coal sample weighing 50 kg was submitted by the company (DEVCO) for the intensive beneficiation testwork. The material was first reduced from 50 mm to 12.5 mm in a conventional jaw crusher. A head sample was then cut and sieved into three sized fractions, which were pulverized and analyzed for ash and sulphur forms (i.e. pyritic, organic and sulphate). The remainder was further crushed to less than 3 mm in preparation for grinding and processing at finer size. The crushing and classification circuit is illlustrated in Fig. 14, while the head analyses are shown in Table 8.

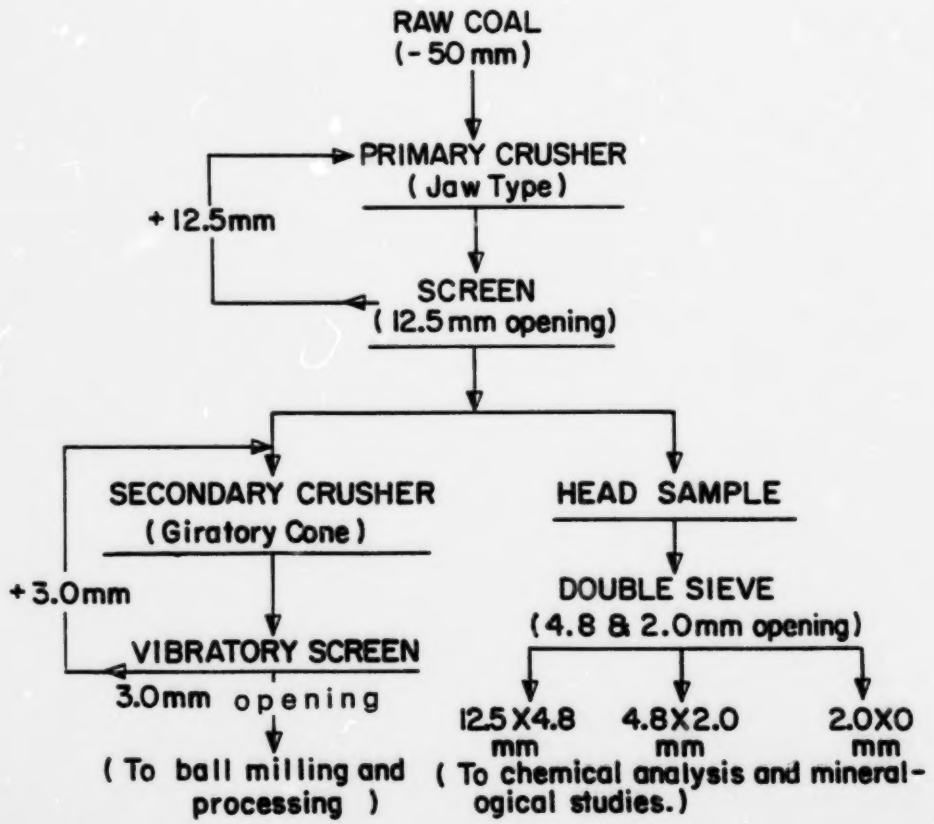

Fig. 14 - COAL CRUSHING AND SAMPLING PROCEDURE

Table 8- Ash and sulphur forms analyses of head sample

Sized fraction (mm)	Weight %	% Ash	Sulphur forms			
			Pyritic % Sp	Organic % So	Sulphate % Ss	Total % St
12.5 x 4.76	27.5	7.12	1.34	1.08	0.08	2.50
4.76 x 2.0	48.5	6.84	1.57	1.22	0.11	2.90
2.0 x 0	24.0	7.91	1.48	0.98	0.44	2.90
Total	100.0	7.17	1.49	1.12	0.18	2.79

The ash, pyritic and organic sulphur are relatively constant. Pyrite accounts for 51.0 to 57.8% of the total sulphur. The sulphate is significantly more abundant in the finest fraction indicating a higher degree of oxidation.

Progressive Grinding and Cleaning

The coal beneficiation procedure was derived from observations made in the mineralogical and dense liquid studies. A first removal of contaminants was made at intermediate size; it was followed by finer grinding and further cleaning stages. After each comminution the coal was exhaustively cleaned by either flotation or high-gradient magnetic separation, and the results compared. The general scheme of the testwork, which involved three levels of grinding and cleaning, namely A, B, and C, is illustrated in Figure 15.

The primary cleaning consist either of one pass through a high-gradient wet magnetic separator or a rougher - 1st cleaner - 2nd cleaner flotation circuit. The three flotation tailings were combined to give total weights comparable to those of the magnetic separation rejects for easier comparison of results. Each flotation stage was carried out until exhaustion using as much MIBC as needed and minimal amounts of kerosene whenever necessary. The results of primary cleaning by froth flotation and magnetic separation are given in Appendix II-A and represented graphically in section A of Figure 16. Since the flotation approach proved to be significantly more effective, subsequent grinding and cleaning were applied only to the concentrates produced by this technique.

The secondary beneficiation also involved magnetic separation versus froth flotation. The two methods gave coal products of comparable grade but the thermal recoveries were generally better with flotation, as is reported in Appendix II-B and shown in Figure 16, section B. The flotation concentrates from the second stage of beneficiation were treated again by comminution followed by both froth flotation and magnetic separation. In this case, the magnetic treatment was more effective (see Appendix II-C and Figure 16, section C).

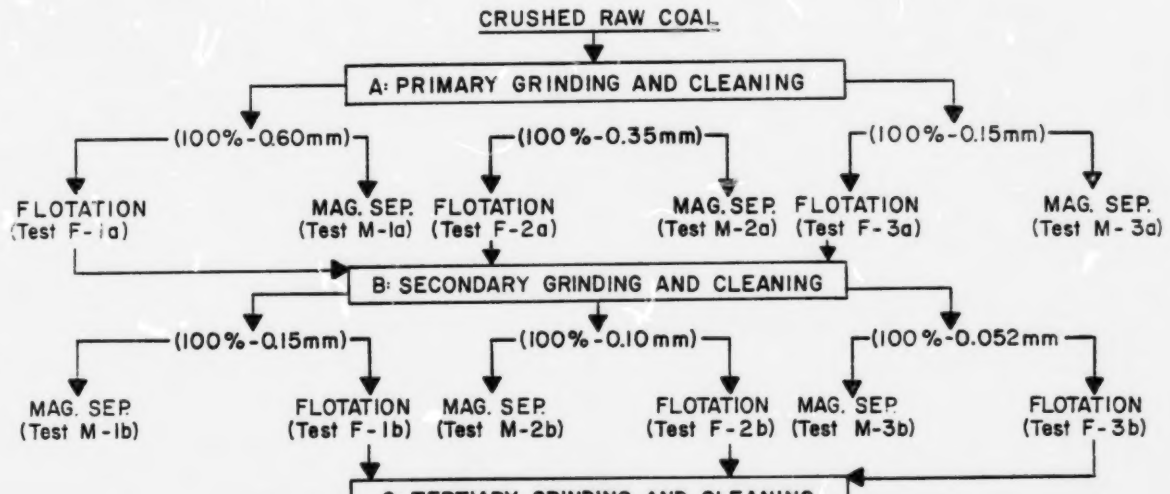

Fig. 15 - GENERAL LAYOUT OF PROGRESSIVE GRINDING AND CLEANING (FLOWSHEET I)

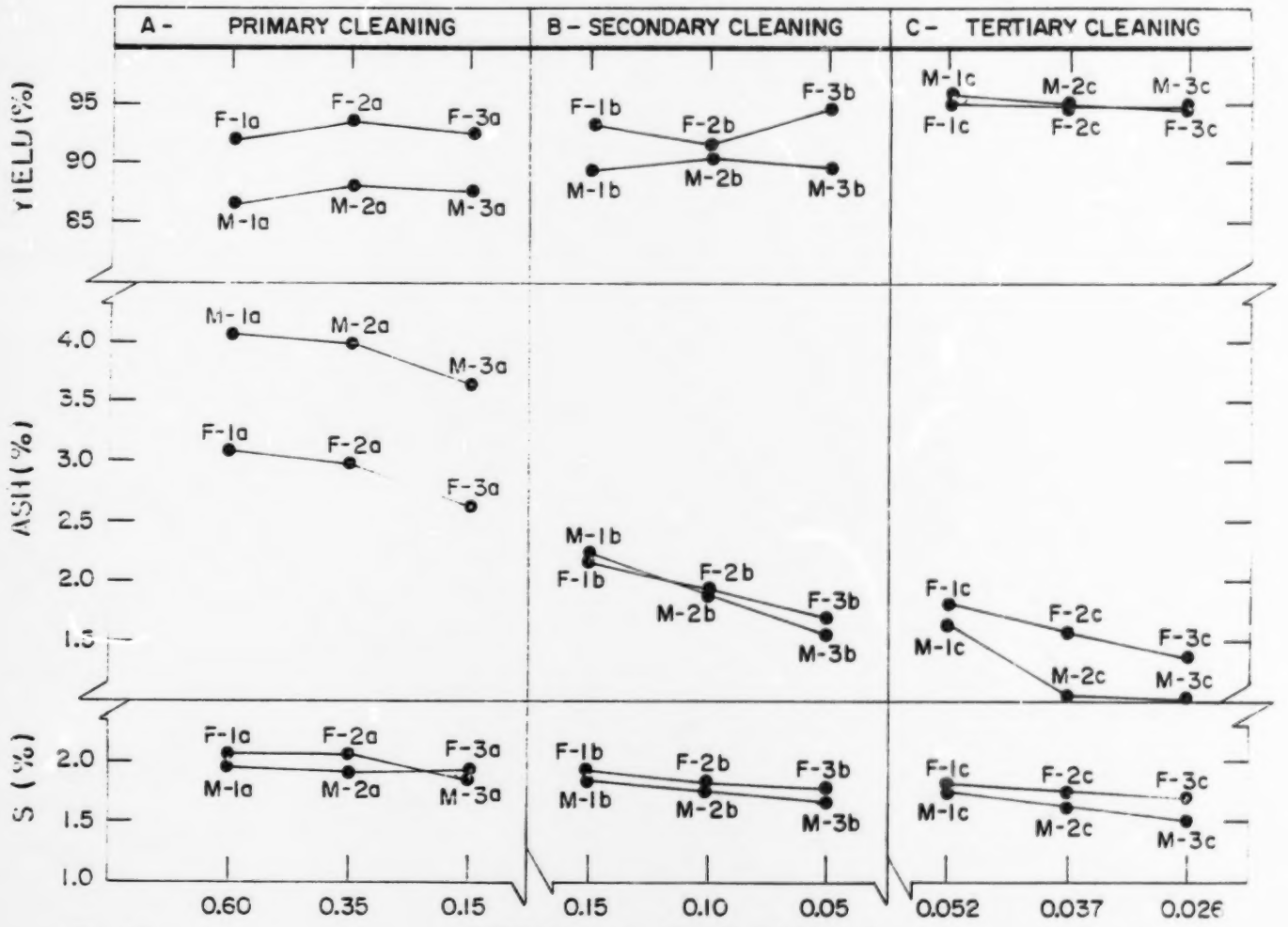

Fig. 16 EFFECT OF FEED SIZE AND DEGREE OF PROCESSING ON THERMAL YEILD, ASH AND SULPHUR CONTENTS

A summary of results integrating various levels of cleaning is given in Table 8; it demonstrate that higher quality coal products are obtainable by finer and progressive grinding and beneficiation, but at the expense of significant thermal losses. A graphical illustration via grade-recovery curves is also shown in Figure 17.

Table 9 - Grade and thermal yield of coal products from flotation and magnetic separation

Grinding (100% minus, mm)			Cleaning procedure			Analysis			Overall thermal yield (%)
1st	2nd	3rd	1st	2nd	3rd	% Asn	% S	BTU	
0.60	-	-	Froth	-	-	3.08	2.07	14358	92.5
0.35	-	-	flota-	-	-	2.96	2.01	14379	93.4
0.15	-	-	tion	-	-	2.62	1.84	14438	92.8
0.60	0.15	-	Froth	Froth	-	2.14	1.90	14523	85.6
0.35	0.10	-	flota-	flota-	-	1.92	1.82	14562	85.5
0.15	0.05	-	tion	tion	-	1.70	1.77	14600	87.9
0.60	0.052	0.052	Froth	Froth	Mag.	1.67	1.76	14606	81.9
0.35	0.037	0.037	flota-	flota-	Sep.	1.06	1.61	14713	81.2
0.15	0.026	0.026	tion	tion		0.98	1.51	14727	83.5

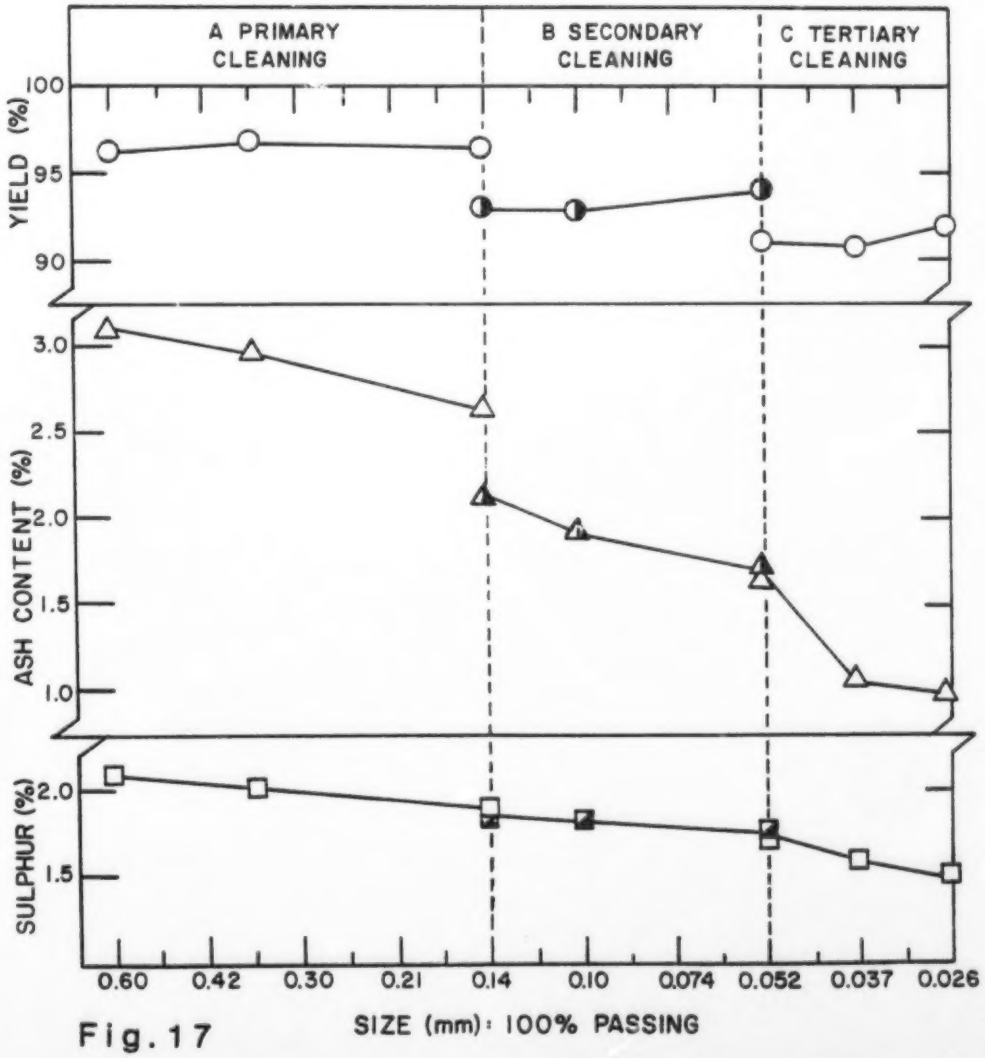

Fig. 17 -INTEGRATED COAL CLEANING RESULTS

Examination of results, as well as curve extrapolation from the primary cleaning towards finer grinding and beneficiation, suggest the possibility of achieving similar yield and quality of coal products while reducing the number of grinding stages. Experimentation towards this aim confirmed this expectation, provided that the final fineness attained minus 44 µm and that magnetic separation was still used after the last froth flotation stage. These observations are exemplified in a series of three tests described in Flowsheet II (Fig. 18), with their analytical results, material and thermal balances recorded in Appendix III. To be directly comparable with washability data, the processing results are also computed on a cumulative basis and the corresponding grade-recovery curves with respect to ash and sulphur are drawn in Figure 19. Comparative float-sink curves from corresponding average size are also shown.

Inspection of the beneficiation curves clearly show a discontinuity and a shift towards the left. This is attributed to greater liberation subsequent to the regrinding stages. This is particularly evident in the case of the ash content. Because of the presence of organic sulphur and of lesser pyrite liberation, the sulphur curves shifting is generally less important. However, their upper sections tend to get more inclined indicating the ability of the magnetic separator to collect middling particles containing a small proportion of pyrite. A sulphur form analysis of the final coal concentrate of Test 6 showed the almost entire removal of the pyrite, with pyritic sulphur being at only 0.16%. Organic sulphur and sulphate were respectively at 1.20% and 0.01% for a total value of 1.37% S; this is somewhat less than to that found in the regular analysis at 1.53% S.

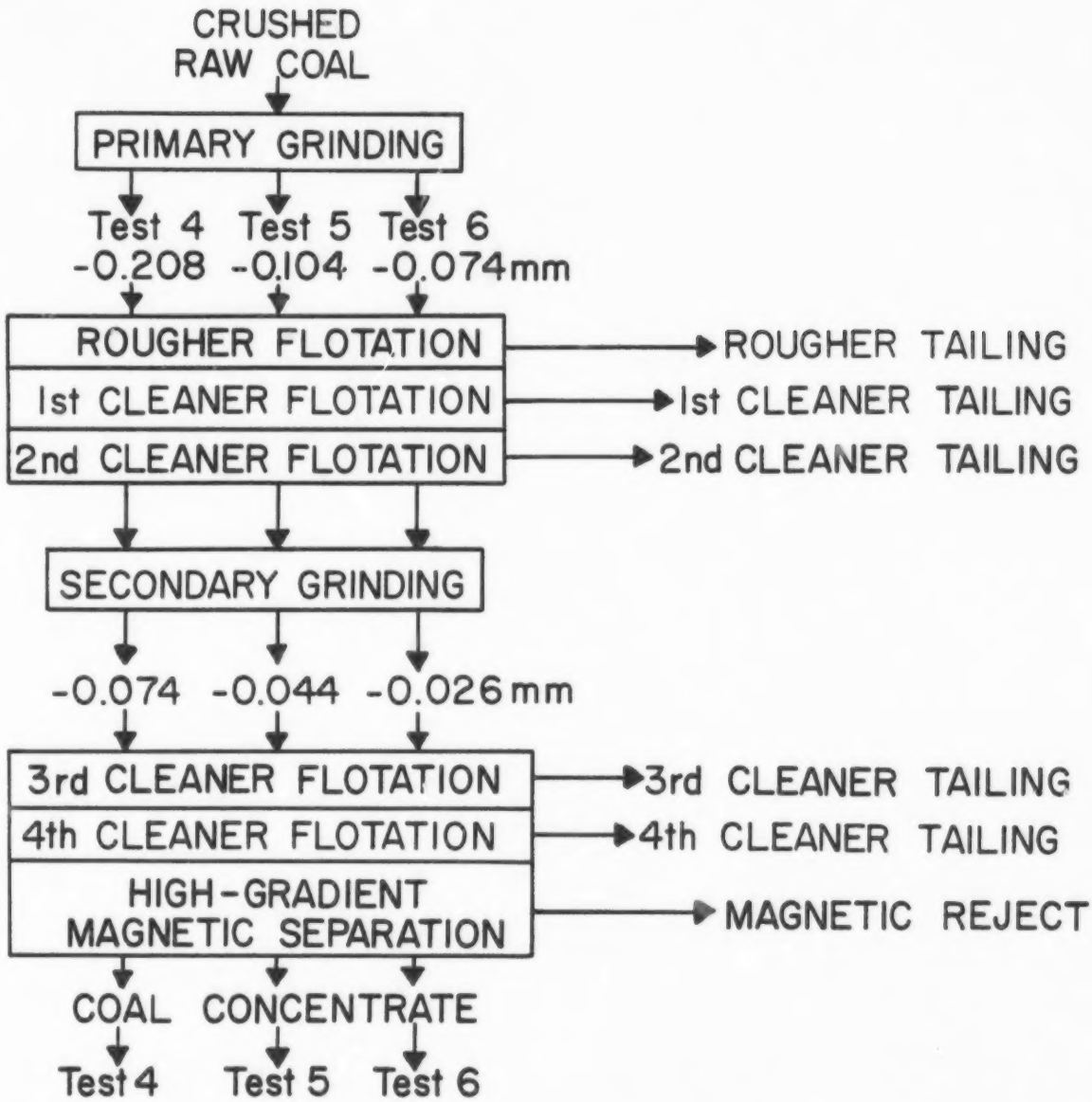

Fig .18- DETAILED LAYOUT OF PROGRESSIVE GRINDING AND PROCESSING (FLOWSHEET II)

Correlation Between Float-Sink
and Flotation-Magnetic Separation

To assess the process efficiency of the flotation and magnetic separation with the Donkin-Morien coal, thermal yields were extrapolated with respect to selected ash and sulphur contents of coal products from both the beneficiation and the float-sink recovery curves; these are compared as a function of size and degree of processing in Table 9. Relative process efficiency, which is defined as the ratio of the thermal yields obtained in beneficiation over that of float-sink, were also calculated at various stages of cleaning and are reported accordingly.

Table 10 - Correlation between flotation-magnetic separation and float-sink

1. Thermal yields and process efficiency at given ash contents

Code*	Data	Flotation-/Float Mag. Sep./ Sink		
A	Mean size (μm)	110/115	61/59	39/32
	Thermal yields at 2.50% ash	87.5e/97.9	91.9/98.2	95.2/98.3
	Process effficiency	0.894	0.936	0.968
B	Mean size (μm)	39/32	26/24	14/16
	Thermal yields at 1.75% ash	84.4/96.4	87.5/96.7	90.1/96.9
	Process efficiency	0.876	0.905	0.930
C	Mean size (μm)	39/32	26/24	14/16
	Thermal yields at 1.25% ash	78.8e/92.1	82.8/93.0	85.2/93.8
	Process efficiency	0.856	0.890	0.908

*The code A, B, C correspond to the primary, secondary and tertiary level of beneficiation by the flotation and magnetic separation.
e = extrapolated

Table 10 - Correlation between flotation-magnetic separation and float-sink (Cont'd)

2. Thermal yields and process efficiency at given sulphur contents

Code*	Data	Flotation-/Float-Mag. Sep./ Sink		
A	Mean size (μm)	110/115	61/59	39/32
	Thermal yields at 1.96% S	92.5e/97.6	95.0/97.4	97.0/97.5
	Process efficiency	0.948	0.975	0.995
B	Mean size (μm)	39/32	26/24	14/16
	Thermal yields at 1.83% S	-	87.7/96.7	90.0/97.2
	Process efficiency	-	0.907	0.926
C	Mean size (μm)	39/32	26/24	14/16
	Thermal yields at 1.65% S	81.5/90.4	83.8/92.1	85.0/93.8
	Process efficiency	0.902	0.910	0.916

*The code A, B, C correspond to the primary, secondary and tertiary level of beneficiation by the flotation and magnetic separation.
e = extrapolated

Size Analysis of Coal Products

Because of the importance of the size-distribution on the rheological properties of the coal-water slurries, size analyses were made on several coal concentrates using a L&N Microtrac unit. The samples selected for illustration correspond to progressively finer coal products from Tests F-2b, 4, M-2c, 5 and 6 (with mean sizes (d_{50}) of 53.7, 39.5, 25.6, 19.5 and 14.3 μm, respectively). The size-distribution data are given in detail in Appendix IV and the corresponding curves are shown in Fig. 20. These are of the gaussian-type with sharper slopes on the right side attributable to the staged grinding procedure.

SUMMARY AND CONCLUSIONS

Chemical, petrological and mineralogical studies have established that the Donkin-Morien is a high-volatile "A" bituminous coal, essentially composed of vitrinite, exinite and semi-fusinite with fine intergrowths and inclusions of kaolinite, illite, pyrite and, to a lesser degree, quartz and calcite. The clay and pyritic minerals also occur occasionally as individual and agglomerated grains, as well as cell fillings and replacements in the macerals. Out of a 2.8% total sulphur contained in the coal tested, some 1.1% is present in organic form and thus not removable by physical means. Furthermore, the pyrite mean size is as fine as 15 µm. The clay minerals account for 7.2% by weight and average 30 µm in size.

Float-sink studies on narrowly sized coal fractions confirmed the necessity of extremely fine grinding for satisfactory removal of the intergrown and locked impurities. The washability tests also showed that the minimum ash and sulphur achievable in coal products would be of the order of 1% and 1.5%, respectively, while sacrificing some 15% of the thermal yield.

The methods selected for coal cleaning were froth flotation and high-gradient magnetic separation. These were tested at progressively finer comminution and their efficiency was compared throughout the procedure. The two techniques were found to be complementary with the flotation being preferably applied in the first beneficiation stages and the magnetic separation in the final cleaning.

The experimental work showed that:

1. Increasing fineness of grinding improved the quality of the coal products and gave higher thermal yields.

2. The progressive processing approach generally gave products lower in ash and sulphur content than those obtained by single grinding and straight flotation at comparable size.

3. A magnetic treatment is necessary for maximum rejection of both ash and pyritic contaminants.

4. The grade improvements due to supplementary cleaner flotation and magnetic separation are obtained at the expense of significant additional thermal losses.

5. The ash and sulphur minerals behaved as predicted from the mineralogical and float-sink data with process efficiencies over 90% at fine sizes and coal products analyzing 1.25% ash and 1.65 sulphur.

ACKNOWLEDGEMENTS

The autnor wishes to acknowledge the assistance in this investigation of P. Prud'homme for grinding and screening, L. Morin for the float-sink separations, R. Campbell for chemical analyses and Microtrac size measurements, and M. Raicevic for the magnetic separation tests. The drawings were made by J. MacLeod. The author is also indebted to M.R. Hughson, CANMET mineralogist, and particularly, to D. Birk and ACI staff for their extensive chemical, mineralogical and densimetric studies. Finally, he is gratefull to DEVCO authorities, who have provided the samples for carrying out this research work.

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APPENDIX I
Summary of float-sink results (cumulative basis)

Sized fractions	Specific gravity	Mass %	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
Coarse: 12.5 x 4.76 and 4.76 x 1.19 (mm)	1.30	76.23	1.78	1.58	14717	19.9	36.7	81.4
	1.35	83.91	2.19	1.77	14630	27.0	45.3	89.1
	1.40	86.62	2.39	1.83	14591	30.4	48.5	91.7
	1.45	89.96	2.79	1.94	14522	36.8	53.4	94.8
	1.50	90.82	2.90	2.01	14502	38.6	55.6	95.6
	1.60	92.63	3.25	2.15	14439	44.1	60.8	97.1
	1.70	93.23	3.40	2.21	14411	46.5	63.0	95.7
	1.80	94.38	3.78	2.32	14342	52.4	66.6	98.2
	2.00	95.38	4.18	2.41	14271	58.5	70.2	98.8
	Sink	4.62	60.82	21.03	3540	41.9	29.8	1.2
	Head (C)	100.00	6.81	3.28	13774	100.0	100.0	100.0
Medium: 1.19 x 0.60 0.60 x 0.35 and 0.35 x 0.15 (mm)	1.30	73.09	1.05	1.41	14488	11.9	38.9	78.6
	1.35	83.47	1.47	1.57	14376	19.1	49.6	89.0
	1.40	87.17	1.70	1.66	14330	23.0	54.6	92.7
	1.45	89.88	1.95	1.77	14285	27.3	60.0	95.2
	1.50	91.02	2.11	1.79	14225	29.8	61.8	96.3
	1.60	92.81	2.42	1.90	14203	34.9	66.5	87.8
	1.70	93.62	2.61	1.94	14170	38.1	68.5	98.4
	1.80	94.34	2.84	1.98	14133	41.7	70.7	98.9
	2.00	95.98	3.47	2.09	14027	51.7	75.5	99.7
	Sink	4.22	73.45	15.33	2041	48.3	24.5	0.3
	Head (C)	100.00	6.43	2.65	13522	100.0	100.0	100.0
Fine: 0.15 x 0.074, 0.74 x 0.037 and 0.037 x 0.026 (mm)	1.30	75.38	0.91	1.51	14740	9.88	35.21	81.23
	1.35	83.06	1.20	1.64	14689	14.32	42.06	89.19
	1.40	86.44	1.39	1.71	14656	17.27	45.73	92.62
	1.45	88.48	1.51	1.76	14634	19.29	48.09	94.66
	1.50	90.25	1.83	1.84	14577	23.43	51.46	96.18
	1.60	91.45	2.08	1.91	14533	27.44	54.04	97.16
	1.70	92.06	2.23	1.96	14506	29.62	55.82	97.63
	1.80	92.68	2.48	2.01	14464	33.12	57.55	98.00
	2.00	94.05	3.05	2.16	14364	41.29	67.76	98.76
	Sink	5.95	68.49	20.23	2846	58.71	37.24	1.24
	Head (C)	100.00	6.94	3.21	13679	100.00	100.00	100.00

APPENDIX II

Results of coal beneficiation along Flowsheet I
A - Primary cleaning
1. Froth flotation

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
F - 1a (0.59 mm)	Coal	86.90	3.08	2.07	14358	35.4	66.4	92.0
	Reject	13.10	37.28	6.95	8339	64.6	33.6	8.0
	Head (C)	100.00	7.56	2.71	13570	100.0	100.0	100.0
F - 2a (0.35 mm)	Coal	87.63	2.96	2.01	14379	32.4	63.7	93.4
	Reject	12.37	43.70	8.07	7209	67.6	36.3	6.6
	Head (C)	100.00	8.00	2.76	13492	100.0	100.0	100.0
F - 3a (0.15 mm)	Coal	86.99	2.62	1.84	14438	29.3	59.7	92.8
	Reject	13.01	42.31	8.32	7453	70.7	40.3	7.2
	Head (C)	100.00	7.78	2.68	13529	100.0	100.0	100.0

2. Magnetic separation (2.1 T, 28 mm/s)

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
M - 1a (0.59 mm)	Coal	83.6	4.35	1.98	14122	52.2	62.8	86.4
	Reject	16.4	20.26	5.99	11334	47.8	37.2	13.6
	Head (C)	100.0	6.96	2.64	13665	100.0	100.0	100.0
M - 2a (0.35 mm)	Coal	85.0	3.98	1.94	14200	50.4	62.9	88.0
	Reject	15.0	22.16	6.45	11000	49.6	37.1	12.0
	Head (C)	100.0	6.70	2.62	13720	100.0	100.0	100.0
M - 3a (0.15 mm)	Coal	84.2	3.64	1.88	14259	45.1	59.3	87.6
	Reject	15.8	23.64	6.88	10739	54.9	40.7	12.4
	Head (C)	100.0	6.80	2.67	13703	100.0	100.0	100.0

APPENDIX II (Cont'd)

B - Secondary cleaning
1. Froth flotation

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
F - 1b (0.15 mm)	Coal	91.91	2.14	1.90	14523	63.9	84.4	93.0
	Reject	8.09	13.76	4.00	12478	36.1	15.6	7.0
	Head (C)	100.00	3.08	2.07	14358	100.0	100.0	100.0
F - 2b (0.10 mm)	Coal	90.48	1.92	1.82	14562	58.7	81.9	91.6
	Reject	9.52	12.84	3.82	12640	41.3	18.1	8.4
	Head (C)	100.00	2.96	2.01	14379	100.0	100.0	100.0
F - 3b (0.05 mm)	Coal	93.65	1.70	1.77	14600	60.8	90.3	94.7
	Reject	6.35	16.19	2.79	12051	39.2	9.7	5.3
	Head (C)	100.00	2.62	1.84	14438	100.0	100.0	100.0

2. Magnetic separation (2.1 T, 28 mm/s)

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
M - 1b (0.15 mm)	Coal	88.3	2.22	1.82	14509	63.8	76.4	89.2
	Reject	11.7	9.49	4.23	13230	36.2	23.6	10.8
	Head (C)	100.0	3.07	2.10	14360	100.0	100.0	100.0
M - 2b (0.10 mm)	Coal	89.2	1.89	1.78	14567	58.6	80.6	90.3
	Reject	10.8	11.03	3.93	12958	41.4	19.4	9.7
	Head (C)	100.0	2.88	1.99	14393	100.0	100.0	100.0
M - 2c (0.05 mm)	Coal	88.3	1.53	1.57	14631	51.7	75.8	89.5
	Reject	11.7	10.78	3.79	13003	48.3	24.2	10.5
	Head (C)	100.0	2.61	1.83	14430	100.0	100.0	100.0

APPENDIX II (Cont'd)

C - Tertiary cleaning

1. Froth flotation

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
F - 1c (0.052 mm)	Coal	95.0	1.83	1.81	14578	81.2	90.5	95.4
	Reject	5.0	8.04	3.61	13480	18.8	9.0	4.6
	Head (C)	100.0	2.14	1.90	14523	100.0	100.0	100.0
F - 2c (0.037 mm)	Coal	94.4	1.57	1.76	14623	77.2	91.2	94.8
	Reject	5.6	7.82	2.83	13533	22.8	8.8	5.2
	Head (C)	100.0	1.92	1.82	14562	100.0	100.0	100.0
F - 3c (0.026 mm)	Coal	94.5	1.36	1.70	14660	75.6	91.8	94.9
	Reject	5.5	7.54	2.97	13572	24.4	9.2	5.1
	Head (C)	100.0	1.70	1.77	14600	100.0	100.0	100.0

2. Magnetic separation (2.1 T, 28 mm/s)

Test (size: 100% passing)	Products	Weight	Analysis			Distribution (%)		
			% Ash	% S	BTU/lb	Ash	S	BTU
M - 1c (0.052 mm)	Coal	95.3	1.67	1.76	14606	79.3	90.4	95.7
	Reject	4.7	8.98	3.82	13320	20.7	9.6	4.3
	Head (C)	100.0	2.01	1.86	14546	100.0	100.0	100.0
M - 2c (0.037 mm)	Coal	94.1	1.06	1.61	14713	54.6	81.2	95.0
	Reject	5.9	14.06	5.71	12425	45.4	18.2	5.0
	Head (C)	100.0	1.83	1.85	14578	100.0	100.0	100.0
M - 3c (0.026 mm)	Coal	94.2	0.98	1.51	14727	55.5	79.6	95.0
	Reject	5.8	12.76	6.23	12654	44.5	20.4	5.0
	Head (C)	100.0	1.66	1.79	14607	100.0	100.0	100.0

APPENDIX III

Results of coal beneficiation using Flowsheet II

Test No. and 100% passing size in mm		Products	Elementary product data							Cumulative data							
			Weight %	Analysis			Distribution %			Products	Weight %	Analysis			Distribution %		
				% Ash	% S	BTU//lb	Ash	S	BTU			% Ash	% S	BTU/lb	Ash	S	BTU
4	0.074	1. Coal conc	76.4	1.52	1.66	14632	16.6	48.9	81.7	1	76.4	1.52	1.66	14632	16.6	48.6	81.7
		2. Mag. reject	4.8	9.22	6.05	13277	6.3	11.1	4.7	1-2	81.2	1.98	1.92	14552	22.9	59.7	86.4
		3. 4th d tail	3.0	7.96	2.35	13499	3.4	2.7	3.0	1-3	84.2	2.19	1.93	14514	26.3	62.4	89.4
	-------	4. 3rd d tail	4.1	16.90	2.68	11926	9.9	4.2	3.6	1-4	88.3	2.87	1.97	14394	36.2	66.6	93.0
		5. 2nd d tail	2.0	12.50	2.25	12700	3.6	1.7	1.9	1-5	90.3	3.09	1.98	14356	39.8	68.3	94.9
	0.208	6. 1st d tail	3.9	17.95	6.49	11741	10.0	9.7	3.3	1-6	94.2	3.70	2.16	14247	49.8	77.0	98.2
		7. Rougher tail	5.8	60.34	9.92	4280	50.2	22.0	1.8	7	5.8	60.34	9.92	4280	50.2	22.0	1.8
		Feed (C)	100.0	6.98	2.90	13676	100.0	100.0	100.0	1-7	100.0	6.98	2.90	13676	100.0	100.0	100.0
5	0.044	1. Coal conc	76.1	1.22	1.59	14685	11.9	43.3	82.6	1	76.1	1.22	1.59	14685	11.9	43.3	82.6
		2. Mag. reject	5.2	9.80	5.35	13175	6.5	9.9	5.1	1-2	81.3	1.77	1.83	14588	18.4	53.2	87.7
		3. 4th d tail	2.1	9.67	3.10	13198	2.6	2.3	2.0	1-3	83.4	1.97	1.86	14553	21.0	55.5	89.7
	-------	4. 3rd d tail	3.5	17.09	2.86	11892	7.7	3.6	3.1	1-4	86.9	2.58	1.91	14446	28.7	59.1	92.8
		5. 2nd d tail	2.5	11.02	4.36	12960	3.5	3.9	2.4	1-5	89.4	2.81	1.97	14404	32.2	63.0	95.2
	0.104	6. 1st d tail	3.2	28.89	7.88	9815	11.9	9.0	2.3	1-6	92.6	3.71	2.18	14245	44.1	72.0	97.5
		7. Rougher tail	7.4	58.98	10.60	4519	55.9	28.0	2.5	7	7.4	58.98	10.60	4519	55.9	28.0	2.5
		Feed (C)	100.0	7.80	2.80	13527	100.0	100.0	100.0	1-7	100.0	7.80	2.80	13526	100.0	100.0	100.0
6	0.026	1. Coal conc	77.8	1.10	1.53	14706	12.1	44.6	83.8	1	77.8	1.10	1.53	14707	12.1	44.6	83.8
		2. Mag. reject	4.8	10.41	6.53	13068	7.1	11.7	4.6	1-2	82.6	1.64	1.82	14611	19.2	56.3	88.4
		3. 4th d tail	3.0	7.40	2.30	13598	3.1	2.6	3.0	1-3	85.6	1.84	1.84	14575	22.3	58.9	91.4
	-------	4. 3rd d tail	2.4	22.52	3.30	10936	7.7	3.0	1.9	1-4	88.0	2.41	1.88	14476	30.0	61.9	93.3
		5. 2nd d tail	3.2	8.85	2.90	13342	4.0	3.5	3.1	1-5	91.2	2.63	1.92	14436	34.0	65.4	96.4
	0.074	6. 1st d tail	1.9	23.35	9.06	10790	6.3	6.4	1.5	1-6	93.1	3.05	2.06	14371	40.3	71.8	97.9
		7. Rougher tail	6.9	61.17	10.92	4134	59.7	28.2	2.1	7	6.9	61.17	10.92	4134	59.7	28.2	2.1
		Feed (C)	100.0	7.07	2.67	13656	100.0	100.0	100.0	1-7	100.0	7.07	2.67	13656	100.0	100.0	100.0

APPENDIX IV

Table 1 - Size analysis of coal concentrates

Size µm \ Sample No.	Size frequency (%).				
	I	II	III	IV	V
176	4.1	-	-	-	-
125	10.0	8.0	-	-	-
88	14.6	13.3	5.9	-	-
62	14.8	14.7	13.0	4.8	-
44	14.1	16.0	16.7	13.7	6.1
31	12.5	13.0	15.7	17.5	13.4
22	9.6	10.5	13.9	16.7	17.9
16	7.5	8.5	10.7	14.6	17.8
11	5.6	6.5	8.2	11.2	14.6
7.8	3.4	4.1	6.0	8.1	10.5
5.5	2.1	2.7	4.4	6.4	8.8
3.9	1.2	1.6	2.8	4.1	6.1
2.8	0.5	1.1	1.7	2.9	4.8
d_{50}	53.7	39.5	25.6	19.5	14.3